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EFFECTS OF WATER INJECTION WITH INCREASED COMPRESSION IN THE INTERNAL COMBUSTION ENGINE

A THESIS

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DEGREE OF M. S.

in

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by

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and

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INTRODUCTION

This investigation was conducted at Georgia School of Technology to determine the effect of water injection in the manifold of an internal combustion engine with an increased compression ratio. The investigation was carried out on a truck engine; first, without changing the compression ratio; and second, with changing the compression ratio by the addition of steel pads to the top of the pistons. The effect of an anti-knock compound was also investigated under the same conditions.

Water injection has been the subject of some past investigation,* but a search of available publications fails to show that any attempt has been made to determine the effect with an increased compression.

* Influence of Water Injection on Engine Performance. National Advisory Committee for Aerovantics Technical Report No.45 (1918)

OBJECT

The results of previous investigations of the effect of water injection into the intake manifold of an engine differ decidedly as to whether or not water injection will give increased power, decreased fuel consumption, decreased carbon deposits and softening of carbon already deposited. Results obtained seem to differ for different makes of engines. Advocates of water injection generally suggest that it will permit operating the engine with a higher compression ratio, although no published data were found in support of this suggestion.

The object of this investigation was to determine from dynamometer tests and indicator diagrams the effect of the injection of water into the intake manifold of an engine on the power output, fuel economy and general engine performance under the following conditions:

1. Engine operating with compression ratio for which it was designed.
2. Engine operating with an increased compression ratio.
3. Both of the above conditions repeated using lead tetra-ethyl gasoline.

APPARATUS

The engine selected for the test was a Packard truck engine, Model 4 D, 4 cylinder, 4 x $5\frac{1}{2}$ inches, with a displacement of 276.4 cu. in. This particular engine was selected because of its availability for test work and the readiness with which the gas engine indicator could be fitted to it. The engine was connected to an air fan dynamometer, the speed of which was taken with a Schaffer and Budenburg tachometer and a Zernickow speed counter. A general view of the test arrangement appears in Figure I, and a schematic drawing is given on Page 24.

Indicator diagrams were taken with a Hopkins flashlight indicator made by the Dobbie McInnes Clyde Company. This instrument is shown mounted over the first cylinder of the Packard engine in Figure 2. In this type of indicator a beam of light is projected from a flashlight at the end of a telescope onto a concave mirror. The mirror is rocked about a horizontal axis by the movement of a piston under the influence of the gas pressure in the cylinder. It is also rocked about a vertical axis by a reducing link work indirectly connected to the crank shaft. The beam of light reflected from this mirror falls upon a photographic plate, thus recording a pressure-volume curve for the cylinder to which the indi-

Figure 1

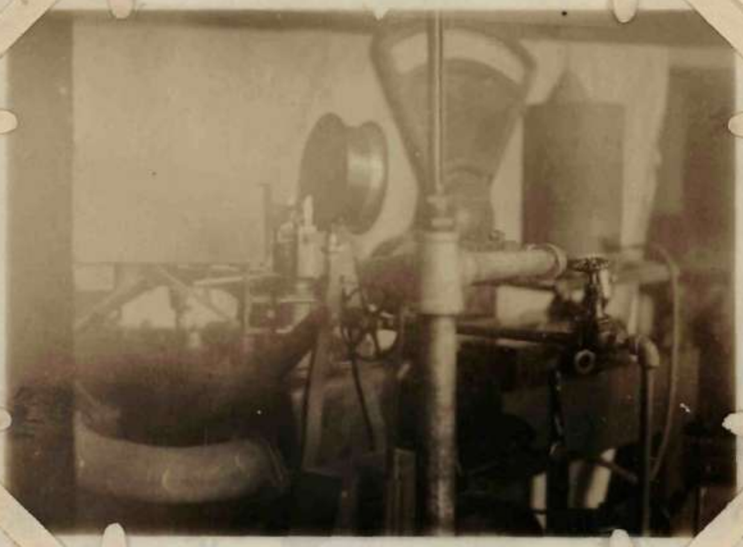


Figure 2

Figure 3

cator is fitted.

The gasoline was weighed on a Toledo springless scale graduated in one-hundredths of a pound.

In order to thoroughly mix the injected water with the fuel mixture it was necessary to develop an atomizing nozzle. A small nozzle similar in design to the type used on a garden hose was first tried. Tests were made with various water pressures and a number of positions of the needle with reference to the orifice. Although a spray of water was formed under certain conditions, this type of nozzle did not prove satisfactory and was erratic in its operation. Twisted flutes were then cut in the orifice and in the needle with the idea of giving the water a rotary motion which might result in sufficient centrifugal force to break up the water particles.

After experimenting with a number of types of nozzles it was found that the best atomization was obtained by impinging a high velocity jet of water against a flat surface perpendicular to the jet. The optimum distance of the orifice from the flat surface depends on the size of the orifice and the water pressure above the orifice. Conditions were also helped somewhat by a hot intake manifold.

During the tests the nozzle was mounted in the intake manifold at the top of the right angle turn from the vertical to the horizontal part leading to the cylinders, as shown in Figure 3. The jet was directed downward toward the carbuerator and impinged upon the inside of the opposite wall of the manifold which presented a flat surface at this point. This location directly in the path of the fuel mixture coming from the carbuerator, together with the fact that the intake manifold was water jacketed assisted materially in thoroughly mixing the water with the fuel mixture. The water was injected at the same temperature as the cooling water entering the engine which varied from 120° to 130°F.

PROCEDURE OF TESTS

Data were taken over three to five minute intervals and included, weight of gasoline, temperature of cooling water entering and leaving the engine, weight of cooling water, temperature of exhaust gases, speed of the fan dynamometer, weight of water injected and an indicator card for each separate condition of operation.

The throttle and spark settings were kept constant throughout all the runs. The amount of water injected was varied by using different water pressures and different sizes of orifices. The water pressure was varied from 50 to 80 pounds per square inch and the amount of water injected varied up to 31.75 pounds per hour where the operation of the engine with normal compression was impaired to the extent of irregularity in the firing of the cylinders and loss of smoothness of operation. An excess of water was also indicated by a distinct drop in the exhaust temperature.

After a series of tests with normal compression, using different amounts of water injection, with gasoline and with lead tetra-ethyl gasoline, the pistons were removed from the engine and a piece of boiler plate was fastened to the top of each piston by means of screws. These plates were the same diameter as the pistons, 1/4 inch thick and contained a 1/2 inch hole in the center which had been used for the purpose of holding the plate on a mandrel for machining. This pad reduced the clearance volume by 3.093 cu.in. and increased the compression ratio to 70 pounds as indicated by an Ashton pressure gage with the engine turning at 100 R.P.M. Before adding the steel pads the compression was 40 pounds by the same method of measurement. All of the previous tests with normal compression were repeated for this higher compression with the exception that the maximum water injection for reliable operation of the engine was found to be 23.02 pounds per hour.

RESULTS AND CONCLUSIONS

A tabulation of data appears later in the report. A set of performance curves plotted with water injected in pounds per brake horsepower hour as the independent variable is shown on page 23. Discussion of the results will be taken up under several different headings.

1. Power Output:

There is a small, gradual reduction in power output as water injection is increased with the engine running under normal compression. The loss in power up to the point where the operation of the engine is impaired amounts to .9 B.H.P. or a reduction of 5.4%. With the engine operating under increased compression there is a decided increase in output as the amount of water injected is increased. When 1.2 pounds of water per B.H.P. hour is being injected there is an increase in power output of 1.8 B.H.P. or 10.8%. It is to be noted that during the test the positions of the throttle and spark were not changed. With the slow rate of combustion obtaining when water is injected, as will be shown later with indicator diagrams, advancing the spark would undoubtedly have resulted in a greater power output. Tests covering this point might be the subject of future experiments. The results therefore indicate a decided increase in power output under increased compression and water injection up to 1.2 pounds of water per B.H.P. hour, but a small loss in power output with water injection and normal compression. The tests with ethyl gasoline did not show any difference in power output at normal compression but a lower power output than Standard Gasoline with water injection and increased compression.

2. Fuel Economy:

With no water being injected and the engine operating with normal compression the gasoline consumption averaged .95 pounds per B.H.P. hour. With water being injected this consumption was steadily reduced reaching a minimum of .84 pounds per B.H.P. hour at a water injection of approximately 1.15 pounds per B.H.P. hour. These figures show a savings of 11/95 or 11.6% in the consumption of gasoline per B.H.P. hour. From a water injection of 1.15 pounds to 2.04 pounds per B.H.P. hour there was an increase in gasoline consumption to a maximum of 1.0 pound per B.H.P. hour. With increased compression the economy is improved a constant amount of approximately 11% over the economy with normal compression. The best economy obtained during the test was with increased compression and water injection of about 1.0 pound per B.H.P. hour. The gasoline consumed under this condition was .75 pounds per B.H.P. hour as compared with .95 pounds per B.H.P. hour with normal compression and no water injection. This is a 21.1% saving in gasoline consumption.

The ethyl gasoline with increased compression gave practically the same results as standard gasoline with water injection of 1.0 pound per B.H.P. hour and increased compression. Injecting water with ethyl gasoline does not better the economy and in some instance it was detrimental.

General:

The effect of water injection on temperature of the exhaust gases is shown by curves on page 23. Until the point of best economy is reached there is very little drop in temperature, but beyond this point the exhaust gas temperature drops rapidly as water injection is increased.

Reduction in the amount of heat carried away by the cooling water was not so pronounced as the drop in temperature of the exhaust. The data show that less heat was carried away by the cooling water during water injection than without any water being injected.

The actual weight of water being injected as compared with the gasoline consumed is of interest since it would indicate the necessary storage space for water should water injection be practicable for road work. The optimum point of operation seems to be at approximately 1.0 pound of water per B.H.P. hour and a gasoline consumption of .75 pound per B.H.P. hour. The ratio of water to gas would be 1.33.

The effect of water injection on the general operation of the engine is to eliminate knock as detected by ear, and increase the smoothness of operation up to the point where enough water is injected to interfere with the firing of the cylinders. This effect is best understood by a study of indicator cards.

A number of theories as to just what knock is have been advanced. Chief among these are the following:

1. The mechanical theory is that knock is actual impact between parts of the engine. This theory, however, does not explain the forces which cause the impact.

2. A pressure-detonation theory explains knock as being due to a very rapid increase of pressure in the engine cylinder so that a portion of the charge is increased to its auto ignition point by the expansion of the portion first ignited. According to this theory fuel should have a tendency to knock in proportion to its spontaneous ignition temperature, which has been proven untrue in a number of instances.

3. A Pressure Wave theory explains knock as the re-

sult of a high velocity-high pressure wave striking against the cylinder walls and piston head. According to this theory knock can take place in most any shape of cylinder or container, with or without a moving piston. This theory has been generally accepted and the results of this experiment partly support it.

The high pressure waves are of such high velocity that the ordinary gas engine indicator cannot follow their movement so that their amplitude can only be calculated and supported by theory. Their presence, however, is shown by a wavy indicator line which shows up best on indicator diagram A, page 30. The use of water injection or ethyl gas smooths out this wavy line as shown in indicator diagram B. These pressure waves did not appear on the diagrams taken with normal compression where there was little or no knock.

The meanings of the terms combustion, explosion and detonation as applied to gas engines have been confusing, but they seem to differ only in the rate of burning. As shown by the pressure-volume indicator diagrams the rise of pressure in the cylinder is slower when water is being injected. Combustion is therefore slower and detonation does not take place.

THEORETICAL DISCUSSION.

A theoretical analysis of the effect of the moisture on the shape of the expansion line was attempted from a standpoint of the behavior of a mixture of moisture in an atomized condition and fuel gases. This analysis was approached from the varying effects on the gases immediately after combustion, the partial pressures of the expansion curve, the pressure at release, and the initial and final temperatures. Because of the complications of such an analysis it was found impossible to satisfactorily complete it in the time available. Work along these lines is suggested as an appropriate subject for another thesis.

In the case of dry gaseous mixtures the theoretical maximum temperature during combustion is easily computed. It is also easy to compute this temperature for dry gaseous mixtures and steam, on the basis of the air standard. However, when water is introduced in the liquid form, the problem is complicated by the lack of information as to the proportion of the constituents of the mixture during combustion, the initial temperature attained, and the partial pressures of the gases of combustion and the steam, whether wet or superheated at that time. It is impossible to determine at what part of the stroke the steam generated from the moisture becomes effective for external work.

The value of "n" was determined from four expansion curves from indicator cards taken under normal and increased compression, with and without water injection. These values are tabulated on page 22 . A series of points was taken on the expansion line starting immediately after the completion of combustion and extending to a point just before release. A value of "n" was also computed using the first and last point on each curve. The average values and the values for each entire curve are tabulated below.

	Normal Compression		Standard Compression	
	With Water	Without Water	With Water	Without Water
Avg. of Series.	1.309	1.391	1.286	1.38
Entire Curve.	1.318	1.41	1.325	1.347

It is to be noted that the value of "n" when water is being injected is lower than the corresponding value without water injection. This is an indication that the expansion curve with water injection is not so steep and the pressure in the cylinder is undoubtedly being sustained by the generation of steam. Indicator cards show that altho the initial pressure in the cylinder is lower for water injection, the pressure does not drop so rapidly due to the partial pressure of the expanding steam and was therefore greater during the latter part of the stroke.

Summary of Results:

The results obtained show that water injected into the intake manifold had the following effects:

1. Decreased the power output 5.4% with the engine running under normal compression.

2. Increased the power output 10.8% with the engine running under increased compression.

3. Reduced gasoline consumption 11.6% with a water injection of 1.15 pounds per B.H.P. hour and the engine running under normal compression.

4. Reduced gasoline consumption 21.1% with water injection and increased compression.

5. Lead tetra-ethyl gasoline showed practically the same increase in power output and decrease in gasoline consumption as standard gasoline with water injection of 1.0 pound per B.H.P. hour.

6. Reduced the exhaust temperature very little up to the point of most economical operation of the engine. Beyond this point the exhaust temperature dropped rapidly.

7. Reduced the amount of heat carried away by the cooling water.

8. Eliminated knock and increased smoothness of operation up to the point where enough water was injected to interfere with the firing of the cylinders.

DATA TAKEN WITH NORMAL COMPRESSION

Time	Gas #/hr	Speed	BHP	Gas,# /BHPhr.	Water Inj'd,# hr.	Water Inj'd,# BHPhr.	Ratio, Water/Gas	Exh. Temp. °F	Jacket cooling 1000 BTU
3:20	16.2	611	16.35	.9908	0	0	0	949	
4:17	15.36	617	16.85	.9115	0	0	0	955	
5:25	14.76	605	15.90	.9283	0	0	0	975	69.98
3:32	16.40	620	17.14	.956	0	0	0	958	73.10
3:42	13.20	617	16.65		0	0	0	954	65.20
5:45	13.68	615	16.70	.8191	6.88	.412	.503	965	66.1
7:41	14.64	609	16.20	.9037	10.85	.671	.741	965	66.10
7:55	14.16	615	16.70	.8479	19.05	1.142	1.345	910	56.38
3:37	13.20	608	16.10	.821	19.05	1.180	1.444	900	60.10
8:41	14.40	613	16.50	.8727	27.02	1.39	1.600	904	56.38
8:49	16.48	601	15.55	.9955	31.75	2.045	2.050	822	48.60

Ethyl Gas

3:50	13.40	614	16.58	.808	0	0	0	966	62.70
3:57	13.60	603	15.70	.856	19.05	1.23	1.400	906	60.10

DATA TAKEN WITH INCREASED COMPRESSION

Time	Gas #/hr.	Speed	BHP	Gas,# /BHPhr.	Water Inj'd,# hr.	BHPhr.	Ratio, Water/Gas	Exh. Temp. °F	Jacket cooling 1000 BTU
6:43	16.2	605	15.9	.9805	0	0	0	837	67.08
1:54	13.56	600	15.5	.8748	0	0	0	842	76.02
6:45	14.04							840	
2:15	13.68	605	15.9	.8603	0	0	0	855	66.23
3:30	13.30	609	16.2	.8209	0	0	0	855	73.5
3:44	13.40	617	16.85	.7952	0	0	0	841	69.74
3:55	14.00	614	16.6	.8433	0	0	0	860	64.10
9:24	14.70	623	17.3	.850	0	0	0	890	64.10
2:35	13.57	615	16.7	.813	0	0	0	857	71.30
3:43	13.20	629	17.9	.737	9.39	.524	.711	869	67.3
3:37	13.80	614	16.6	.8313	9.72	.586	.704	841	67.86
2:48	13.00	616	16.75	.776	10.19	.604	.784	844	75.2
9:29	14.20	630	17.9	.794	23.02	1.285	1.62	790	66.0
2:23	13.04	600	15.50	.841	13.69	.883	1.05	832	56.19
3:35	13.60	635	18.4	.739	16.40	.891	1.206	856	61.40
5:05	13.20	636	18.50	.714	16.40	.887	1.243	867	67.3
2:58	13.5	633	18.25	.740	19.05	1.044	1.41	859	67.30
3:50	13.9	640	18.90	.7354	19.8	1.048	1.42	865	62.20
				Ethyl Gas					
4:17	13.65	631	18.00	.758	0	0	0	895	73.30
4:24	13.90	637	18.60	.748	9.38	.503	.678	903	69.30
4:31	13.20	630	17.95	.736	19.05	1.061	1.443	867	65.30

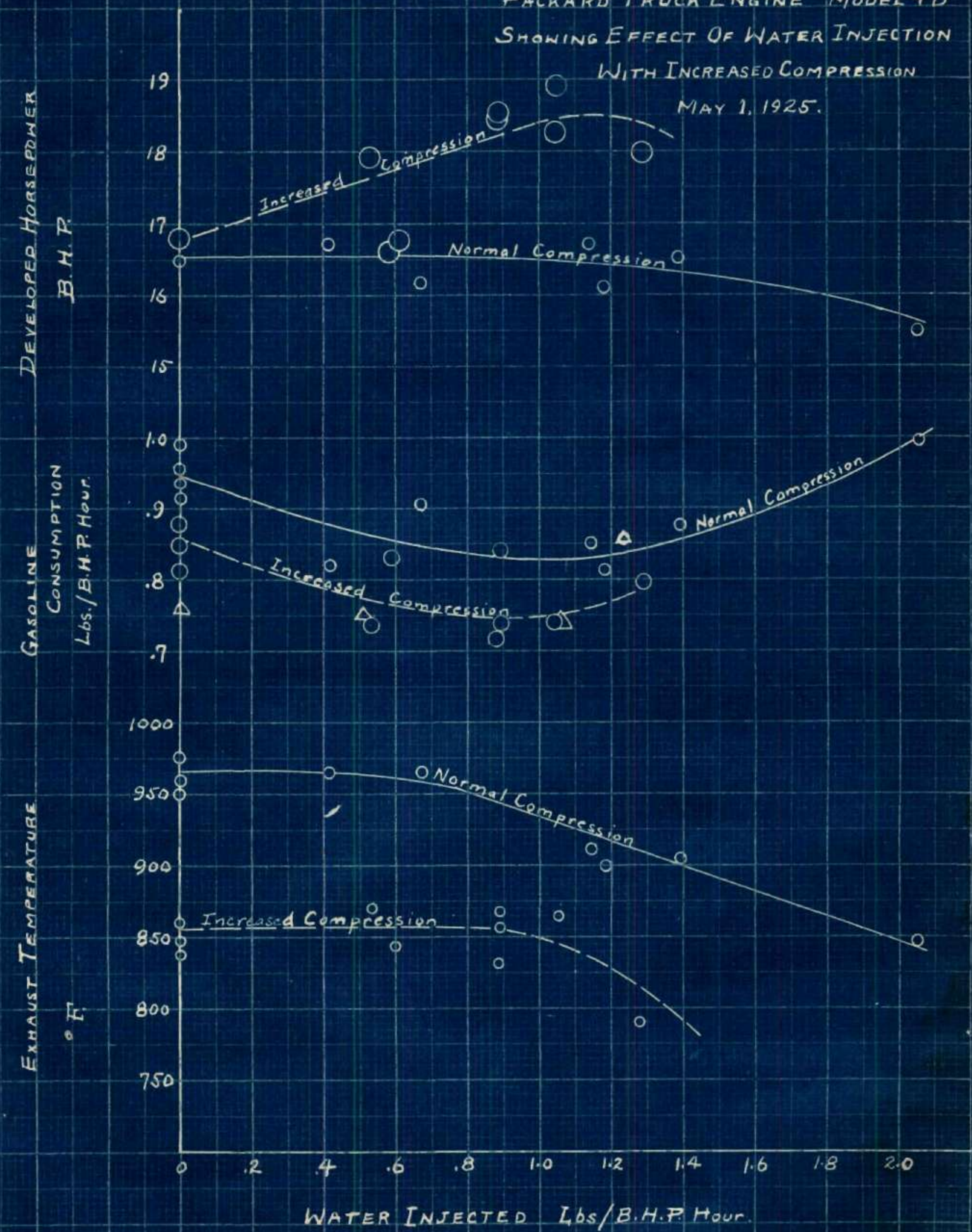
Card 30 Normal Compression Without Water

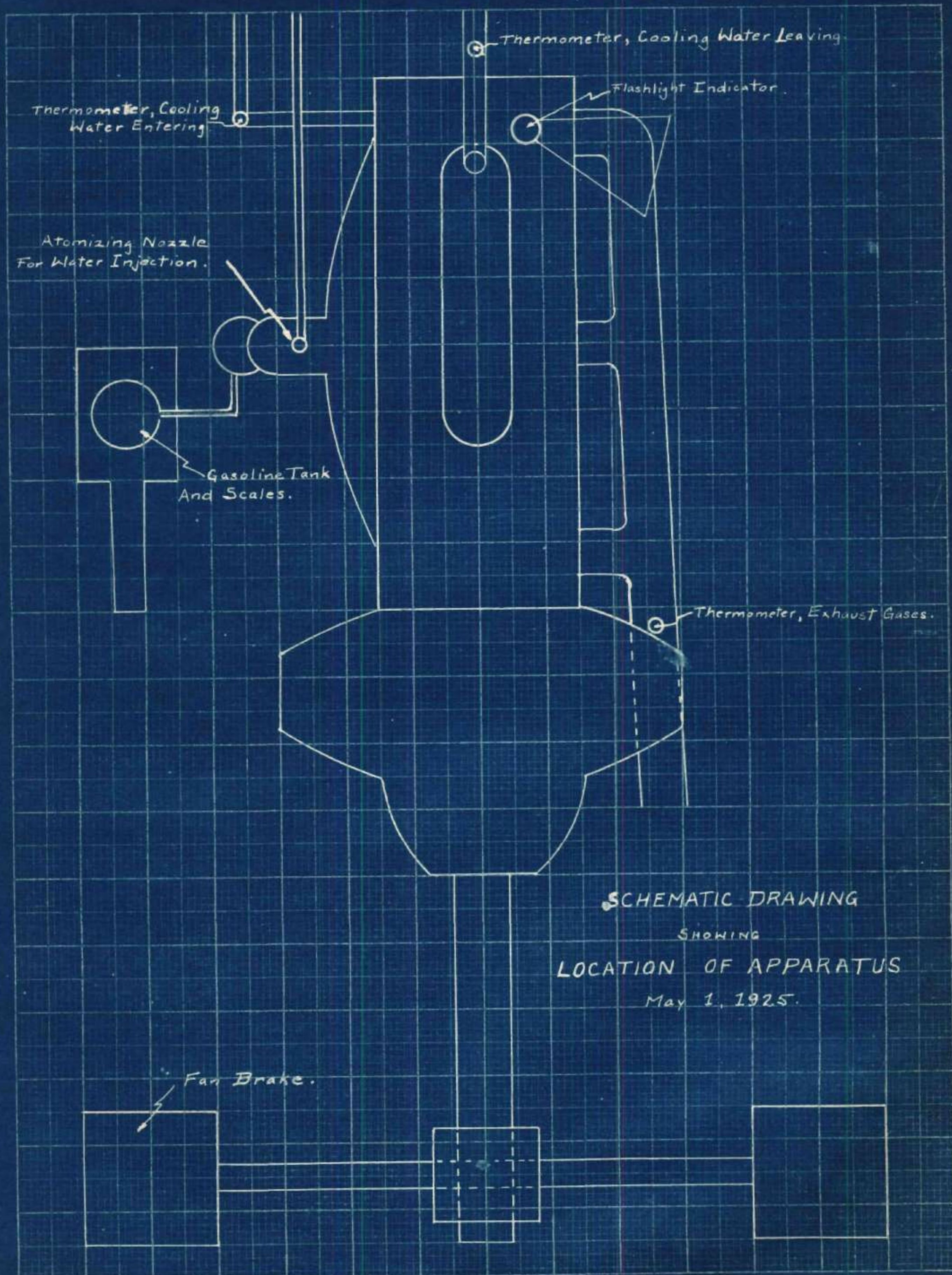
Pt	V	P.	Ratio $V_n:V_{n-1}$	Ratio $P_{n-1}:P_n$	"n"	Avg."n"
1	1.62	2.03				
2	1.8	1.78	1.111	1.153	1.35	
3	2.02	1.53	1.122	1.163	1.312	
4	2.25	1.28	1.115	1.195	1.635	
5	2.52	1.10	1.12	1.162	1.325	
6	2.93	.88	1.162	1.25	1.485	
7	3.26	.77	1.113	1.142	1.24	1.391
1-6			1.808	2.308		1.41
Card #4					With Water	
1	1.63	2.01				
2	1.82	1.74	1.117	1.155	1.30	
3	2.21	1.34	1.214	1.298	1.345	
4	2.78	.99	1.258	1.353	1.32	
5	3.39	.77	1.219	1.285	1.27	1.309
1-5			2.08	2.61		1.318

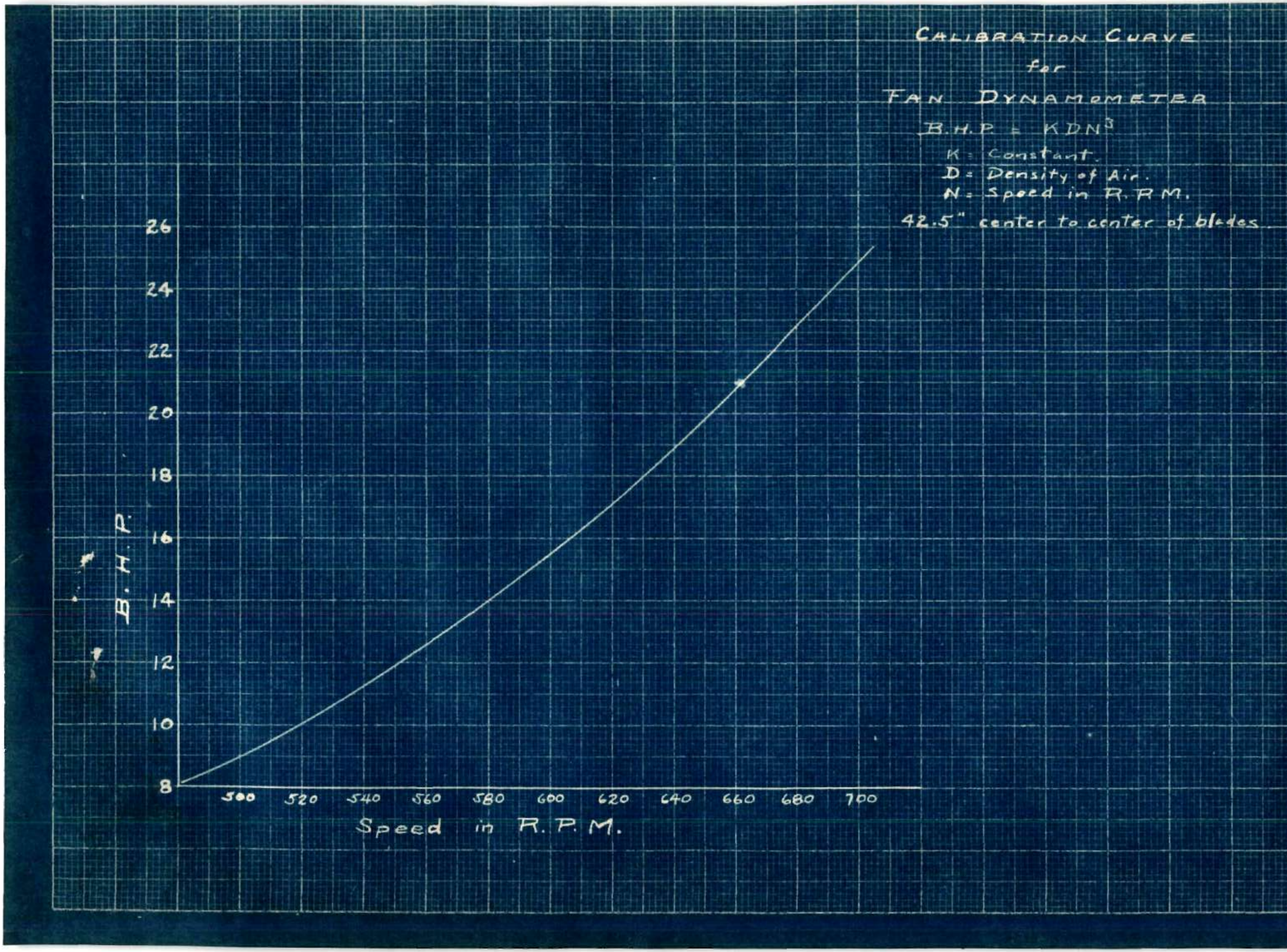
Card #A Increased Compression Without Water

1	1.70	2.06				
2	2.11	1.57	1.241	1.325	1.303	
3	2.59	1.19	1.227	1.32	1.355	
4	3.19	.90	1.232	1.323	1.342	
5	3.73	.71	1.169	1.268	1.52	1.38
1-5			2.19	2.903		1.347
Card #B					With Water	
1	2.05	1.83				
2	2.38	1.48	1.161	1.237	1.425	
3	2.79	1.22	1.172	1.213	1.220	
4	3.17	1.02	1.135	1.195	1.410	
5	3.76	.79	1.187	1.291	1.490	1.286
1-5			1.834	2.31		1.325

PERFORMANCE CURVES
PACKARD TRUCK ENGINE MODEL 4D
SHOWING EFFECT OF WATER INJECTION
WITH INCREASED COMPRESSION
MAY 1, 1925.



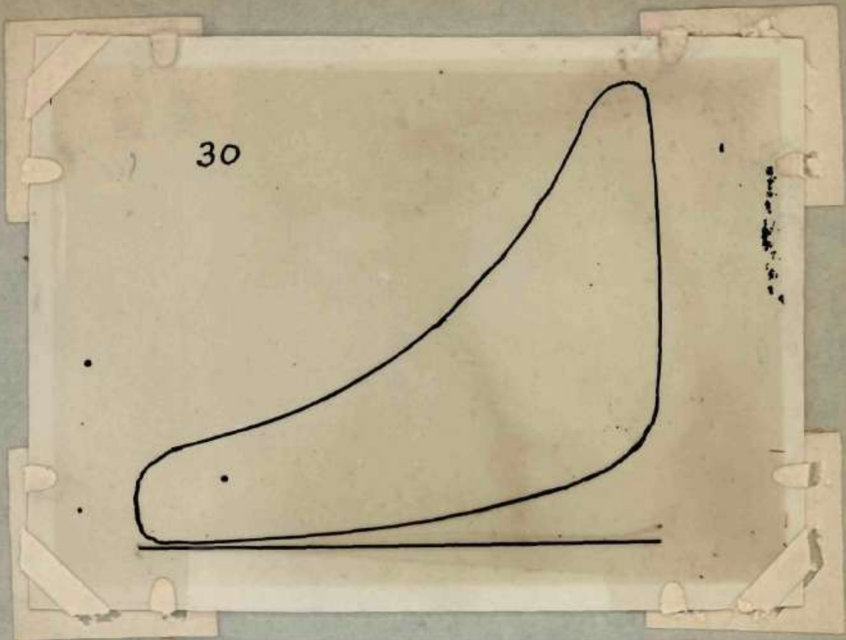

Thermometer, Cooling Water Leaving
Flashlight Indicator
Thermometer, Cooling Water Entering
Atomizing Nozzle For Water Injection.
Gasoline Tank And Scales.
Thermometer, Exhaust Gases.
SCHEMATIC DRAWING
SHOWING
LOCATION OF APPARATUS
May 1, 1925.
Fan Brake.


CALIBRATION CURVE
for
FAN DYNAMOMETER
B.H.P = KDN^3
K = Constant.
D = Density of Air.
N = Speed in R.P.M.
42.5" center to center of blades.
B. H. P.
26
24
22
20
18
16
14
12
10
8
500
520
540
560
580
600
620
640
660
680
700
Speed in R.P.M.

No.30

Normal Compression
Without Water Injection

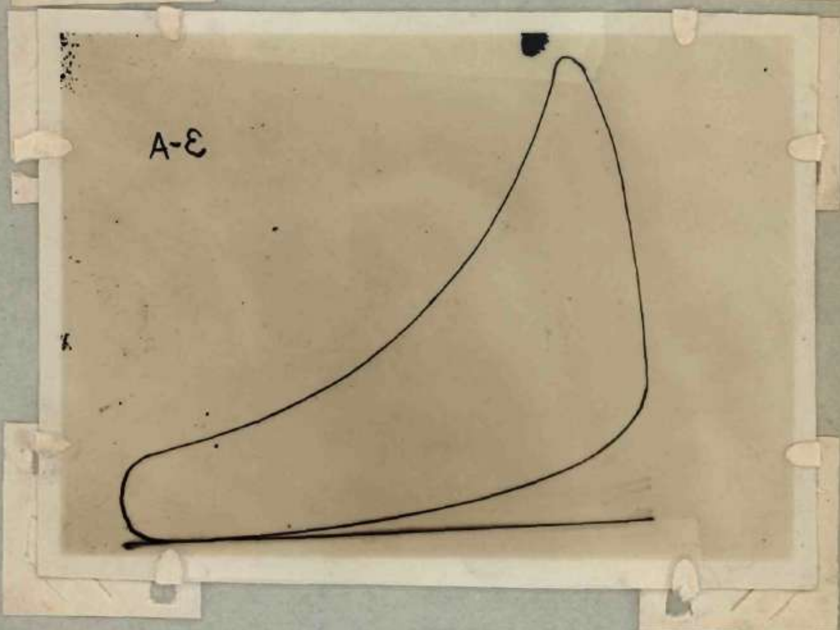
Avg.Height 1.03"
M.E.P. 83.7 lbs.
Speed 620.5 R.P.M.
B.H.P. 17.14



No.3a

Normal Compression
Water Injected
.671#/B.H.P. hr.

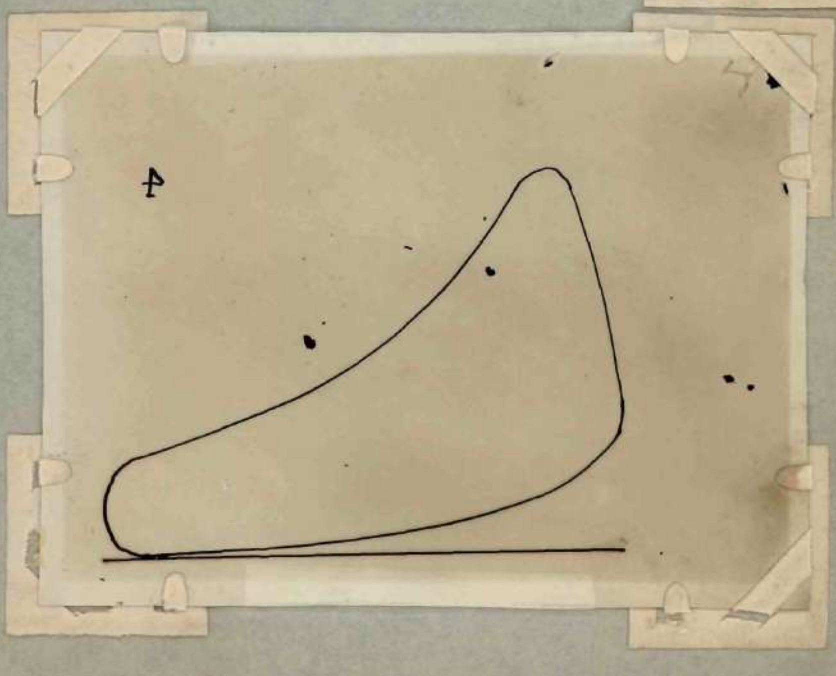
Avg. Height 1.01"
M.E.P. 82.8 lbs.
Speed 609 R.P.M.
B.H.P. 16.2



No.4

Normal Compression
Water Injected
1.142#/B.H.P. hr.

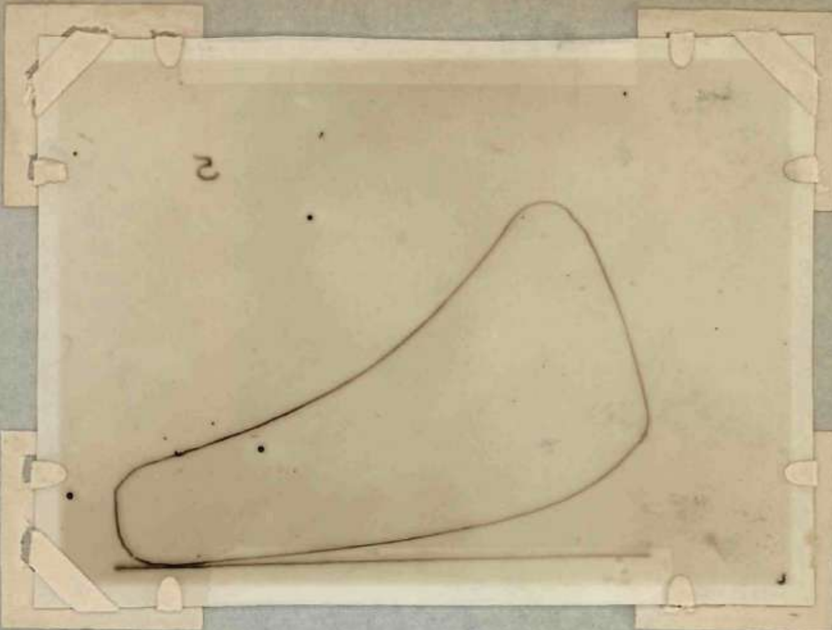
Avg.Height .958"
M.E.P. 79.5 lbs.
Speed 615 R.P.M.
B.H.P. 16.7



No.5

Normal Compression
Water Injected
1.39#/B.H.P. hr.

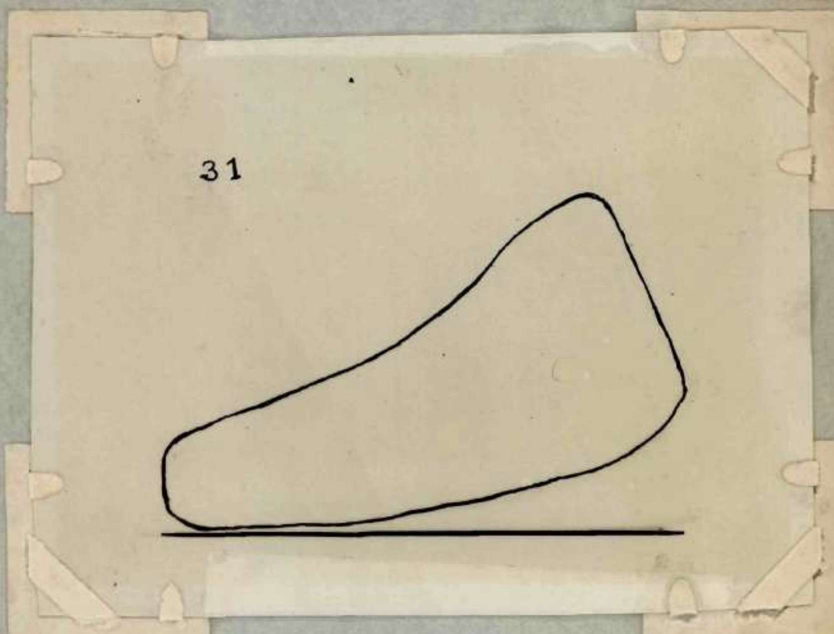
Avg.Height .938"
M.E.P. 77.75 lbs.
Speed 613 R.P.M.
B.H.P. 16.5



No.31

Normal Compression
Water Injected
1.18#/B.H.P. hr.

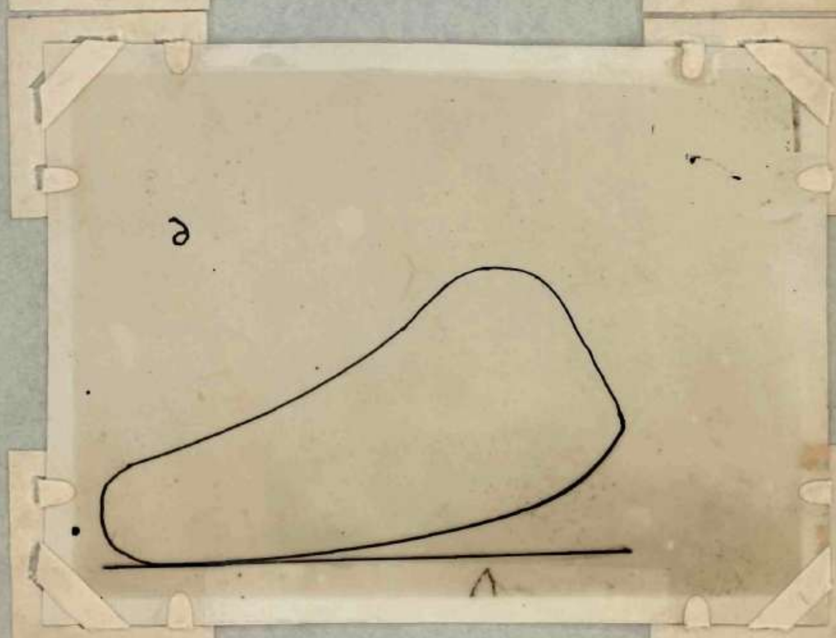
Avg.Height .898"
M.E.P. 74.5
Speed 608 R.P.M.
B.H.P. 16.1



No.6

Normal Compression
Water Injected
2.045#/B.H.P. hr.

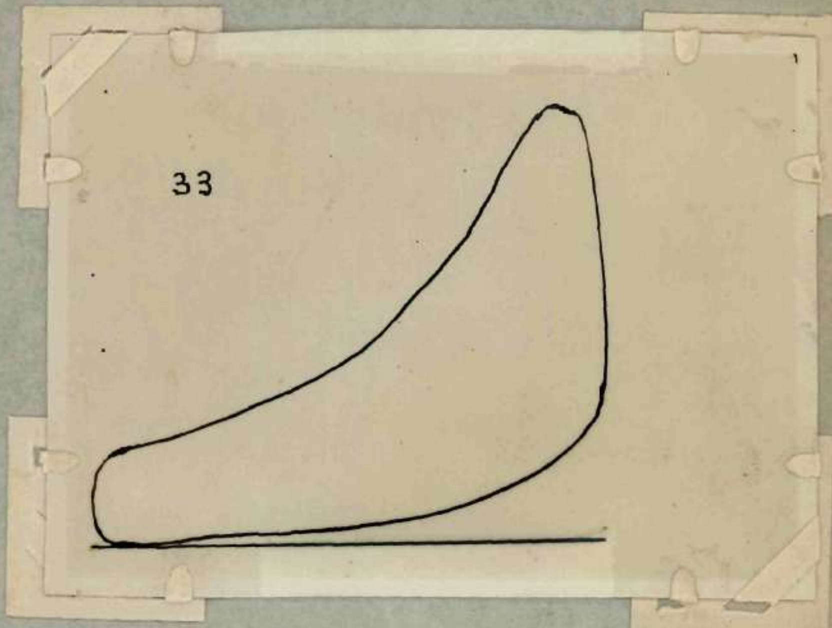
Avg.Height .862"
M.E.P. 71.5
Speed 601 R.P.M.
B.H.P. 15.55



No.33

Normal Compression
Ethyl Gasoline
No Water Injected

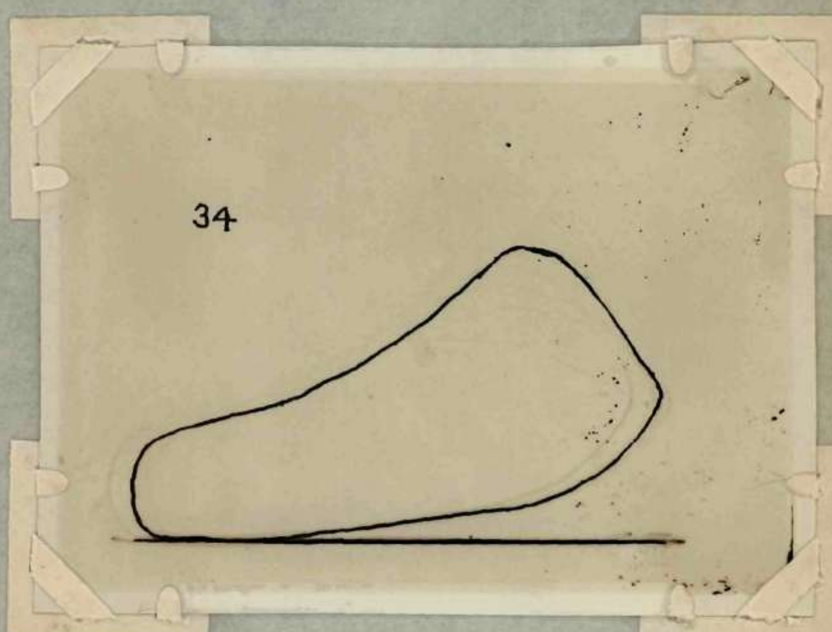
Avg. Height .988"
M.E.P. 81.0 lb.
Speed 614 R.P.M.
B.H.P. 16.58



No. 34

Normal Compression
Ethyl Gasoline
Water Injected
1.23#/B.H.P. hr.

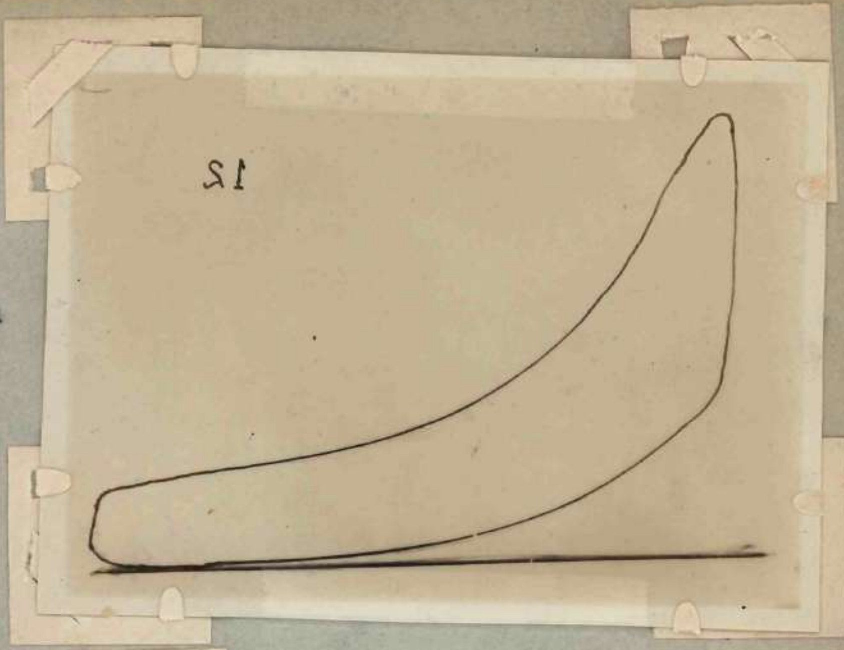
Avg.Height .852"
M.E.P. 69.9 lbs.
Speed 603 R.P.M.
B.H.P. 15.7



No.12

Increased Compression
No Water Injected

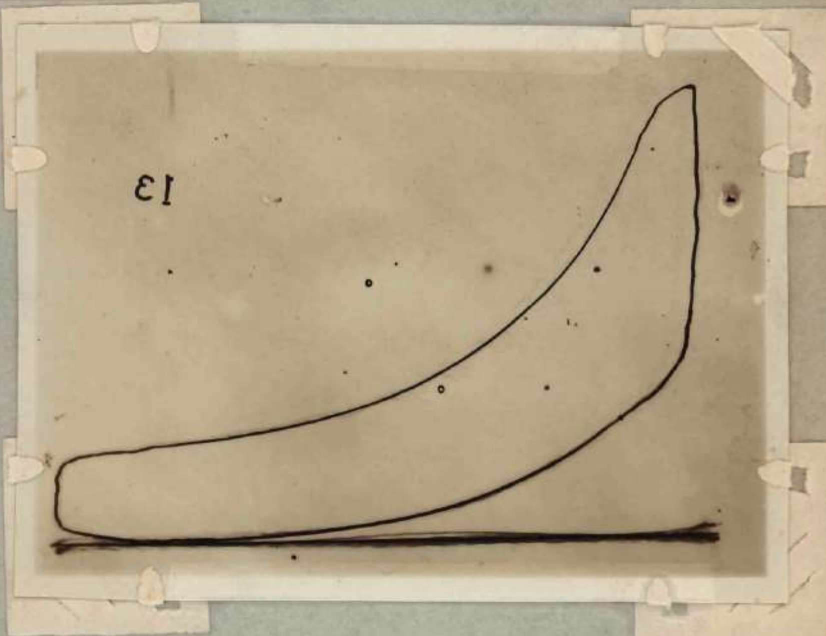
Avg.Height 75.5"
M.E.P. 62.7
Speed 620 R.P.M.
B.H.P. 17.1



No.13

Increased Compression
Water Injected
.586#/B.H.P. hr.

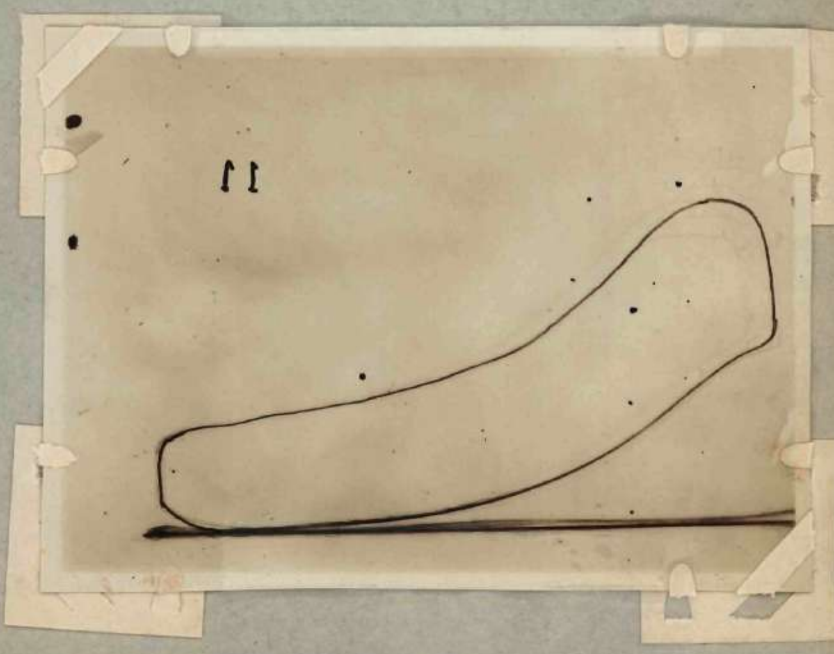
Avg.Height .744"
M.E.P. 61.8 lbs.
Speed 614 R.P.M.
B.H.P. 16.6



No.11

Increased Compression
Water Injected
.883#/B.H.P.hr.

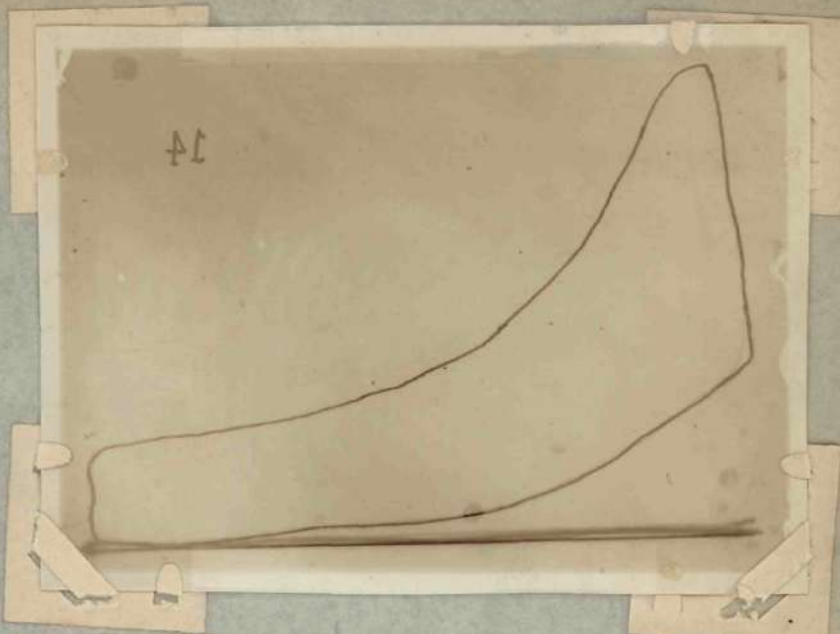
Avg.Height .726"
M.E.P. 60.2
Speed 600
B.H.P. 15.5



No.14

Increased Compression
Water Injected
1.048#/B.H.P.hr.

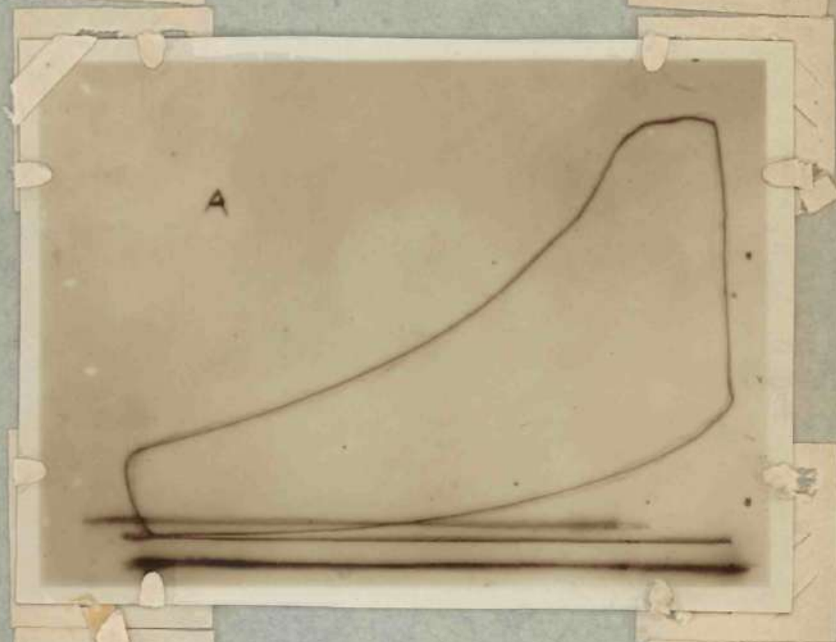
Avg.Height .889
M.E.P. 73.8 lbs.
Speed 640 R.P.M.
B.H.P. 18.9



A

Increased Compression
No Water Injected

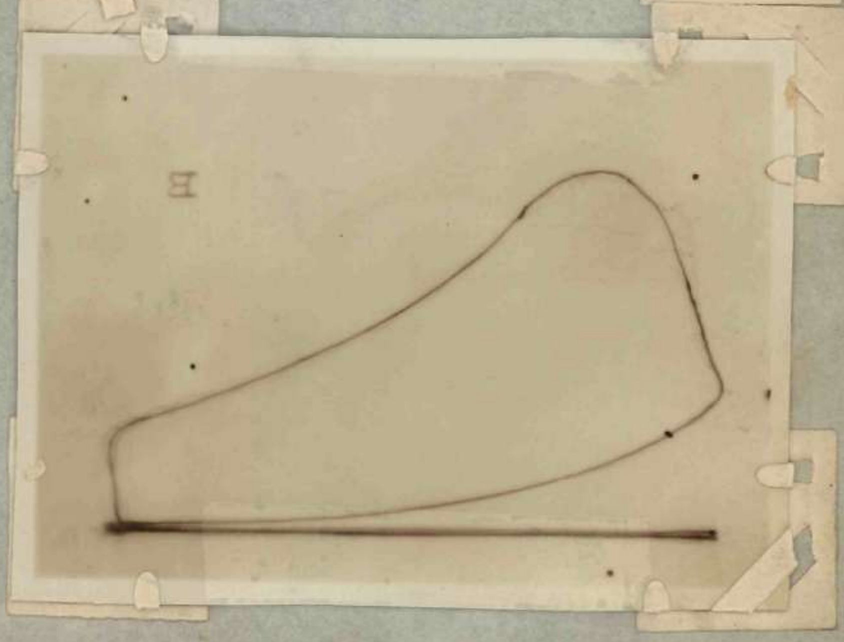
Avg.Height 1.07"
M.E.P. 88.9 lbs.
Speed 623 R.P.M.
B.H.P. 17.3



B

Increased Compression
Water Injected
1.285#/B.H.P. hr.

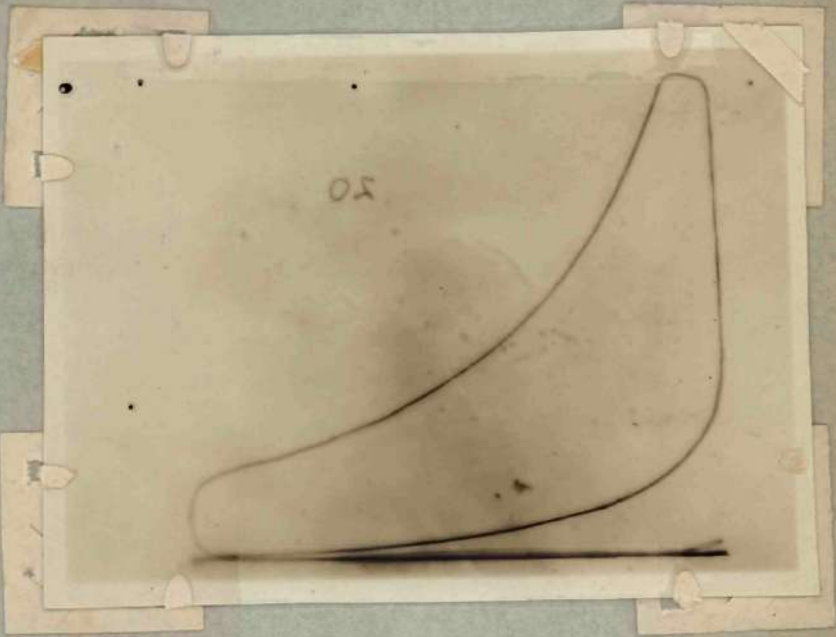
Avg.Height .968"
M.E.P. 80.4
Speed 630 R.P.M.
B.H.P. 17.9



No. 20

Increased Compression
Ethyl Gasoline
No Water Injected

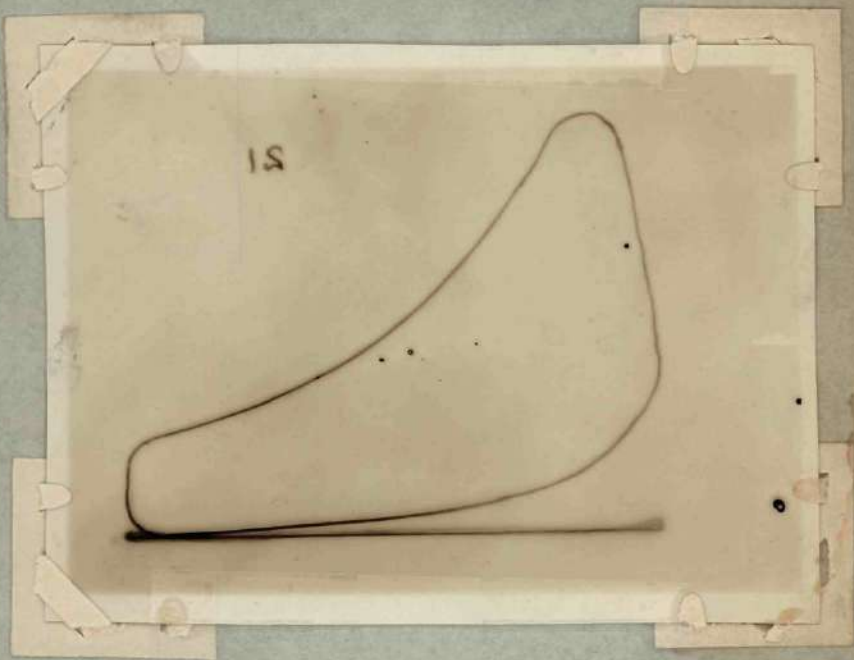
Avg. Height 1.002"
M.E.P. 82.2 lbs.
Speed 631 R.P.M.
B.H.P. 18.0



No. 21

Increased Compression
Ethyl Gasoline
Water Injected
1.061#/B.H.P.hr.

Avg. Height 1.026
M.E.P. 84.1 lbs.
Speed 630.5 R.P.M.
B.H.P. 17.95



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